

Study of Refrigerator Coupled to Water Heater and a Heating Floor

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Abstract

With an aim to make rational use of energy, energy safety, and to reduce carbon emission, our interest was geared towards the refrigerators such as R134a freon and all the refrigerating machines. Indeed the heat yielded by the exchanger condenser can be developed for the water heating, floors heating etc. After an encouraging theoretical study, two prototypes were produced in order to validate the theoretical results. The first refrigerator was coupled with a water-heater and the other with a heating floor. Without modifying the temperature of the evaporator, which is at approximately -20°C , the water temperature reached, in one day, is of 60°C ; which makes it possible to predict better results with a continuously used refrigerator. In the same way for the heating floor coupled with the second refrigerator, the temperature reached high values (50°C), because the surface is reduced; however for the heating floors the standard fixes the temperature between 28 and 30°C .

Key words

Refrigerator; Recuperator; Heating Water; Heating Floor; Heat Pump

Nomenclature

COP	coefficient of performance
C_p	heat mass ($\text{J kg}^{-1}\text{C}^{-1}$)
h	heat exchange coefficient ($\text{Wm}^{-2}\text{K}^{-1}$)
M	Mass (kg)
P_{comp}	power of the compressor (W)
Q	Heat quantity (J)
S	surface (m^2)
t	time (h)
U	convection losses coefficient ($\text{Wm}^{-2}\text{K}^{-1}$)
S	surface (m^2)
T	Temperature ($^{\circ}\text{C}$)
ΔT	Temperature variation ($^{\circ}\text{C}$)
Δt	time variation (s)
η	efficiency
ρ	density (kg/m^3)
λ	conductivity transfer coefficient ($\text{Wm}^{-1}\text{K}^{-1}$)
Signes	
amb	ambient
i	initial
f	final
th	thermal
fr	refrigerator

Introduction

Energy consumption in the world is significant and in continuous growth. It is fundamentally linked to the living quality. It promotes the thermal comfort of the citizens, through the heating and cooling systems (air-conditioners, water-heaters, refrigerators etc. With the aim of saving energy and reducing carbon emission, it is necessary to find some innovating solutions in this field to create negawatts.

For this reason, it is proposed to recover the waste heat on the refrigerator condenser level, by two methods:

- The first method is to enhance the heat lost during condensation of Freon, and then recovered in a water cumulus to heat and use in the domestics or other needs
- the second method consists in heating a floor to replace the traditional heating radiators.

Finally, the heat recovery system does not have any modification on the basic refrigeration cycle. The tests and experiments show the effectiveness of this heat recovery project [Ben Slama (2009-2010)].

Bibliographical Study

The publications evoking the use of heat pumps for water heating are relatively very few. Let us quote Grazini, Skrivan, Huang, Jie who extracted heat from the ambient air like cold source of the heat pump. Figure 1 is given as an example.

Others authors use solar energy like evaporator such as Hawlader, Li, Chyng, Borges, Huang. Among the few publications jointly using the condenser and the evaporator of a heat pump (or refrigerator), we even quote our work concerning a solar sea water still developed by our self, at the National School Engineers of Gabes, Tunisia [Ben Slama (2006-2007)], [Hidouri (2010)].

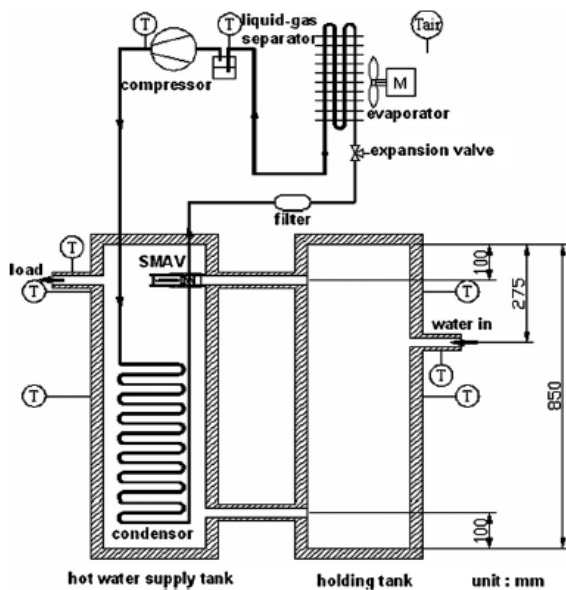
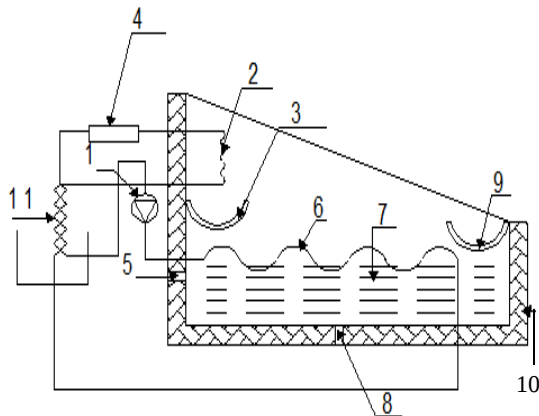


FIG. 1 WATER HEATING BY HEAT PUMP



- 1: Compressor. 2: evaporator. 3: gutter. 4: valve.
 5: opening of filling. 6: condenser. 7: sea water.
 8: opening of draining. 9: gutter. 10: insulator. 11: economizer.

FIG. 2 SOLAR DISTILLER PROVIDED WITH HEAT PUMP

Figure 2 shows our system of solar desalination provided with the heat pump.

The condenser (6) heats water to be evaporated and the evaporator (2) makes it possible to condense instantaneously the vapour and thus forming the condensate collected in the gutter (3).

For the principle of refrigerator operation (fig. 3), this system can be considered as an insulated cupboard whose interior temperature is lower than the ambient temperature. To obtain cold inside the refrigerator, heat is extracted with the air and food and then rejected by the condenser in the kitchen.

Theoretical Considerations of the Coupling of Refrigerator to a Water-heater and a Heating Floor

It was started by determining the intervals of real

operating time of the refrigerator and the heat transfer between the condenser and water or floor to be heated.

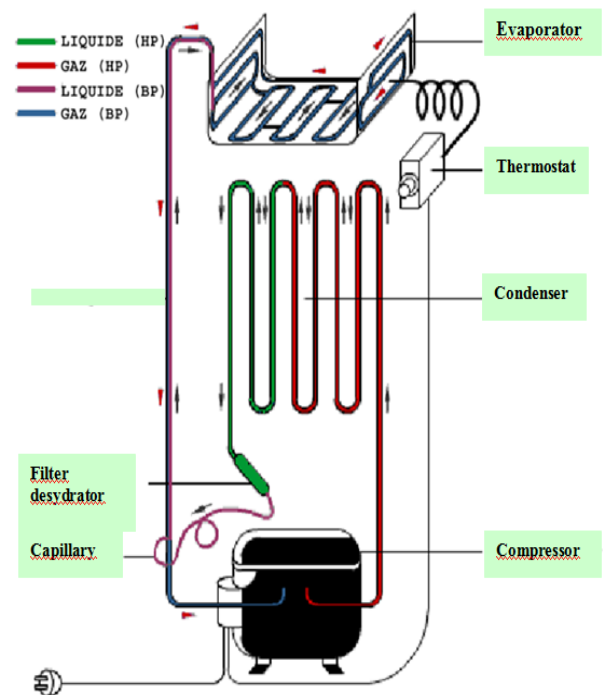


FIG. 3 REFRIGERATOR OPERATION CYCLE

Preliminary Study of Dimensioning

The tracing of the histogram of figure 4 allows knowing the operating time of refrigerator' compressor during 24 hours. The operating time varies from moment as required by the refrigerator.

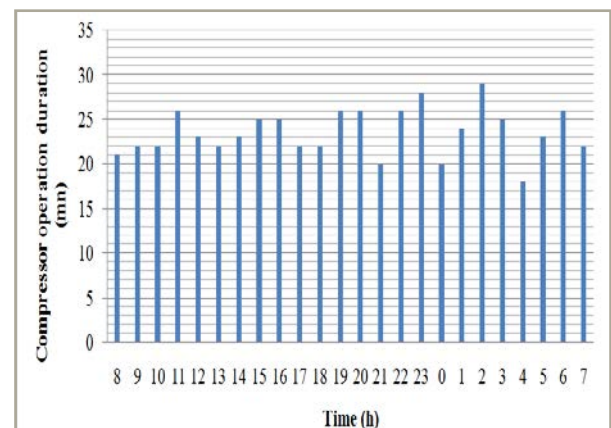


FIG. 4 TIME OPERATION LIFE OF A REFRIGERATOR LASTING 24H

Operation of a refrigerator during 24 hours. Compressor power of 140W and using R13a freon. Room temperature = 19 °C. (Tozeur, Tunisia, on march 20, 2009).

$$\sum t_{\text{compressor}} = 9 \text{ h } 43 \text{ min /day}$$

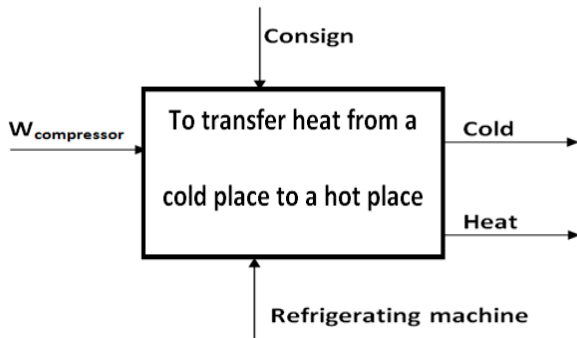
Theoretical Study of a Refrigerator to a Water-heater Coupling

The energy yielded by the condenser is transferred to

water to be heated. However, when water heats in the storage tank, thermals loss will appear (coefficient $U = 4.92 \text{ W/}^\circ\text{C}$).

1) Modeling

The refrigerating machine can be modeled by considering energies on the level of the compressor, the condenser and the evaporator, as follows:



The first law of thermodynamics makes it possible to write:

$$P_{\text{comp}} - Q_{\text{condenser}} + Q_{\text{evaporator}} = 0$$

$$P_{\text{comp}} - P_{\text{comp}} \cdot \text{COP}_{\text{th}} + P_{\text{comp}} \cdot \text{COP}_{\text{fr}} = 0$$

$$1 - \text{COP}_{\text{th}} + \text{COP}_{\text{fr}} = 0$$

$$\text{COP}_{\text{total}} = \text{COP}_{\text{th}} + \text{COP}_{\text{fr}}$$

The total COP can thus reach raised values, which confers on our system a great energetic effectiveness, because, usually the refrigerating machine is used either like refrigerator to produce the cold, or like heat pump to heat.

2) Thermal Transfer

For the coupling of a refrigerator to a water cumulus study, we make the calculation of the water mass which can be heated with different temperatures and evaluate the thermal efficiency. It is supposed that the heat yielded by the condenser is recovered by water to heat except that around the efficiency.

$$Q_{\text{condenser}} = Q_{\text{water}}$$

$$\text{COP} \cdot P_{\text{comp}} \cdot t \cdot \eta = M_{\text{water}} \cdot C_p \cdot \Delta T \quad (1)$$

ΔT is the water temperature increase from initial to final state.

It is possible to determine the variation of ΔT according to time, in the same way for the efficiency.

- Determination of heat water storage efficiency

$$\eta = Q_{\text{useful}} / Q_{\text{absorbed}} \quad (2)$$

With

- $Q_{\text{absorbed}} = P_{\text{comp}} \cdot \text{COP} \cdot t$
- $Q_{\text{useful}} = Q_{\text{abs}} - Q_{\text{loss}}$
- $Q_{\text{loss}} = U \cdot \Delta T \cdot t$

P_{comp} : compressor power.

t : summon operating time of compressor.

U : thermal losses ratio

$$U = \frac{Q \cdot C_p \cdot V}{\Delta t} \cdot \ln \left(\frac{T_i - T_{\text{am}}}{T_f - T_{\text{am}}} \right) \quad (3)$$

With:

$$C_p \text{ water} = 4185 \text{ J/ (kg}^\circ\text{C)}$$

$$\rho \text{ water} = 1000 \text{ kg/m}^3$$

$$\Delta t = 11 \text{ hours ; } (18 :00 \rightarrow 5 :00)$$

$$V = 0,05 \text{ m}^3$$

$$T_i = 59^\circ\text{C}; T_{\text{am}} = 26^\circ\text{C}$$

$$T_f = 35^\circ\text{C}; T_{\text{am}} = 22^\circ\text{C}$$

$$U = 4,92 \text{ W/}^\circ\text{C}$$

Therefore, we have:

$$\eta = \frac{P_{\text{comp}} \cdot \text{COP} \cdot t - U \cdot \Delta T \cdot t}{P_{\text{comp}} \cdot \text{COP} \cdot t} = 1 - \frac{U \cdot \Delta T}{P_{\text{comp}} \cdot \text{COP}} \quad (4)$$

- Temperature variation

We replace (4) in (1), then:

$$\Delta T = \frac{P_{\text{comp}} \cdot \text{COP} \cdot t}{U \cdot t + M_{\text{water}} \cdot C_p} \quad (5)$$

- Mass of water to heat

Replacing (5) in (4), so:

$$M_{\text{water}} = \frac{P_{\text{comp}} \cdot \text{COP} \cdot t}{\Delta T \cdot \left(\frac{C_p}{\Delta T} \cdot \ln \left(\frac{T_i - T_{\text{amb}}}{T_f - T_{\text{amb}}} \right) \cdot t + C_p \right)} \quad (6)$$

The calculation of the water mass to heat, during 24 hours, can be carried out for different water temperature rise.

According to expression (6) we give table 1.

TABLE 1 VALUE OF WATER MASS FOR DIFFERENT RISE IN TEMPERATURE

ΔT ($^\circ\text{C}$)	20	25	30	35	40
M (kg)	90	72	60	51	45

TABLE 2 VARIATION OF ΔT AND EFFICIENCY ACCORDING TO TIME

Time (hours)	ΔT ($^\circ\text{C}$)	efficiency	Q_{useful} (J)	Q_{abs} (J)
6	14,20	0,83	2972654	3565800
12	24,35	0,71	509736	7131600
18	32	0,62	6691162	10697400
24	38	0,55	7930746	14263200
48	52,50	0,38	10986005	28526400
72	60,22	0,29	12604349	42789600

3) ΔT Variation and Efficiency According to Time for Water Capacity of 50 Liters which is the Experimentally Capacity Used.

According to the expressions (2) and (3) we calculated the temperature rise, the efficiency, the

useful and absorptive energies, gathered in the following table 2 and figure 5.

With $P_{\text{comp}} = 140 \text{ W}$; $\text{COP} = 3$; $M_{\text{water}} = 50 \text{ Kg}$

With time, water warms up by the heat yielded by the condenser; then, the quantity of heat contained in water increases. However, the energetic efficiency decreases following the increase in the losses by convection with the ambient air (fig.5).

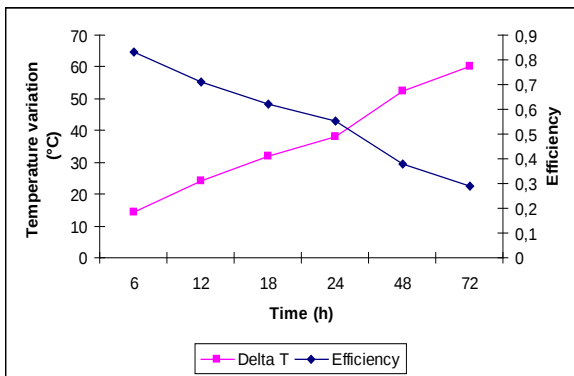


FIG. 5 RISE VARIATION IN WATER TEMPERATURE ACCORDING TO TIME

4) Checking Length of the Condenser Immersed in the Hot Water Cumulus

In our case, the flow of the refrigerant (R134a freon) in the condenser immersed in the cumulus is done from top to bottom, i.e. in against current with the circulation of the water to be heated which is done upwards.

Therefore the difference in logarithmic average temperature curve will be carried out in an against current cycle (figure 6).

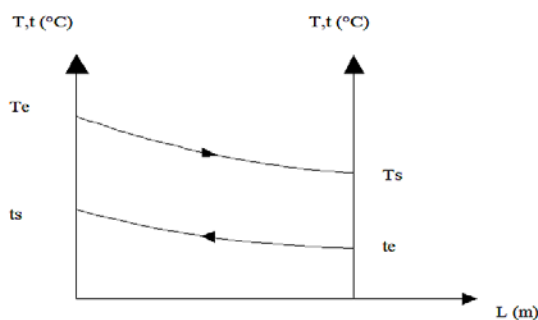


FIG. 6 CYCLE OF AGAINST CURRENT

According to table 2 of comparison during 12 hours and according to measurements:

- Hot source: (condenser)
 $T_e = 62 \text{ °C}$ and $T_s = 43 \text{ °C}$
- Cold source : (water to be heated); with ($\Delta T = 24,35 \text{ °C}$)
 $t_e = 20 \text{ °C}$ and $t_s = 44,35 \text{ °C}$

- Determination of the logarithmic average temperature difference ΔT_{mL}

It's known that the expression of ΔT_{mL} is:

$$\Delta T_{mL} = \frac{\Delta T_0 - \Delta T_L}{\ln\left(\frac{\Delta T_0}{\Delta T_L}\right)} \quad (7)$$

$$\Delta T_0 = T_e - t_s = 62 - 20 = 42 \text{ °C}$$

$$\Delta T_L = T_s - t_e = 43 - 20 = 23 \text{ °C}$$

$$\Delta T_{mL} = 20,16 \text{ °C}$$

- Heat exchange coefficient:

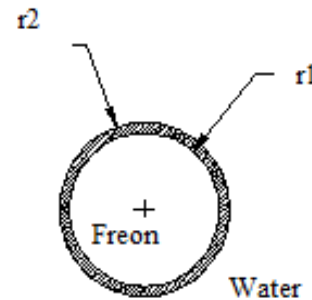


FIG. 7 HEAT EXCHANGER (WATER CONDENSER)

The condenser exchanger contains freon which passes from vapor state to liquid state by yielding its heat to water to be heated (figure 7).

$$U_i = \frac{1}{\frac{1}{h_{\text{freon}}} + d_i \cdot \frac{\ln\left(\frac{d_e}{d_i}\right)}{2\lambda_{\text{copper}}} + \frac{1}{h_{\text{water}}}} \quad (8)$$

With:

$$h_{\text{water}} = 50 \text{ W/(m}^2\text{°C)}; h_{\text{freon}} = 4200 \text{ W/(m}^2\text{ °C)}$$

$$\lambda_{\text{copper}} = 390 \text{ W/(m °C)}$$

$$d_i = 0,004 \text{ m}; d_e = 0,006 \text{ m}$$

$$\text{Then: } U_i = 50 \text{ W/(m}^2\text{ °C)}$$

Theoretical Study of the Coupling of a Refrigerator to a Heating Floor

In this section, we will make the study of a refrigerator to a heating floor coupling, and the determination of the temperature variation for each surface for different periods and for different surfaces to be heated.

Calculation is carried out on concrete surfaces height $h = 0.1 \text{ m}$.

There is a thermal contact between two bodies thus there is a heat transfer between the two bodies in contact (condenser/ concrete).

$$Q_{\text{condenser}} = Q_{\text{concrete}} \quad \text{COP} \cdot P_{\text{comp}} \cdot t \cdot \eta = M_{\text{concrete}} \cdot C_p \cdot \Delta T \quad (9)$$

ΔT : variation between the final and the initial temperature of the floor.

- Determination of the temperature variation ΔT

Like equation (2), we have:

$$\eta = Q_{\text{useful}}/Q_{\text{absorbed}} = Q_{\text{absorbed}} - P_{\text{loss}}/Q_{\text{absorbed}}$$

With:

- $Q_{\text{absorbed}} = P_{\text{comp}} \cdot \text{COP} \cdot t$
- $P_{\text{loss}} = U \cdot S \cdot \Delta T \cdot t$
- $Q_{\text{useful}} = Q_{\text{absorbed}} - P_{\text{loss}}$

The initial temperature is equal to the ambient temperature.

Thus, like equation 4,

$$\eta = 1 - \frac{U \cdot \Delta T}{P_{\text{comp}} \cdot \text{COP}} \quad (10)$$

Replacing (10) in (9):

$$\Delta T = \frac{P_{\text{comp}} \cdot \text{COP} \cdot t}{U \cdot t + M_{\text{concrete}} \cdot C_p} \quad (11)$$

With: $M_{\text{concrete}} = \rho \cdot S \cdot H$

Finally:

$$\Delta T = \frac{P_{\text{comp}} \cdot \text{COP} \cdot t}{U \cdot t + \rho \cdot S \cdot H \cdot C_p} \quad (12)$$

Table 3 and figure 8 indicate the variations of ΔT according to time and the floor surface.

TABLE 3 VARIATION OF ΔT ACCORDING TO TIME AND OF SURFACE

Surface (m ²)	ΔT (°C)			
	1 day	2 days	3 days	7 days
1	26	32	35	38
3	8.7	10	11	13
5	5.2	6	7	7
10	2.6	3.2	3.5	3.8
15	1.7	2.1	2.3	2.6
20	1.3	1.6	1.7	2

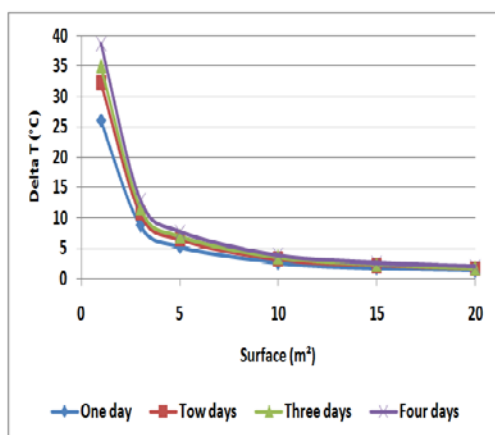


FIG. 8 FLOOR TEMPERATURE RISE ACCORDING TO SURFACE AND A NUMBER OF DAY

The reached temperature on the floor level is a function of the exchange surface with the condenser; in fact also with the compressor power.

In practice, a prototype of heating sand floor of surface $S = 0.43 \text{ m}^2$ was produced and in which a condenser of

6 m length is immersed there.

Experimental study

First, we make the water cumulus then its coupling with the refrigerator and the heating floor.

Water Cumulus Realization

We have a cylindrical tank in plastic, diameter 0.38 m and height 0.48 m, which is isolated by 5 cm glass wool. The unit is then covered by a thin stainless steel jacket (figure 9).

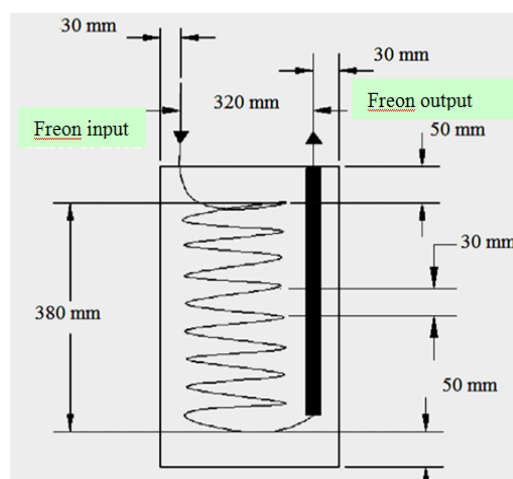


FIG. 9 DIMENSIONS OF THE COPPER CONDENSER IMMERSED IN THE WATER CUMULUS

Coupling between the Refrigerator and the Water Cumulus

We replaced the refrigerator condenser by a copper spiral serpentine placed in the water cumulus, thus the freon condensation will allow yielding the latent heat to water and thus constituting a hot water storage (figure 10, 11).

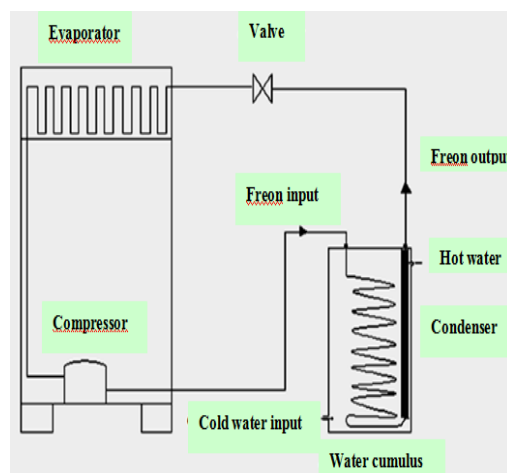


FIG. 10 REFRIGERATING CIRCUIT BINDING THE REFRIGERATOR AND THE WATER-HEATER



FIG. 11 COUPLING OF THE REFRIGERATOR TO A WATER-HEATER PHOTOGRAPH

Heating Floor Realization

The goal for the moment is to construct a transportable prototype. Thus the floor is carried out by some sand filling of a wood box of dimensions 0.66 m x 0.66 m, that is to say a surface of 0.43 m². As the selected height is 0.1 m, then the sand mass is:

$$M = \rho \cdot S \cdot H = 66.6 \text{ Kg.}$$

The condenser of refrigerator is then placed in the wood box before filling this latter by dry sand (figure 12).

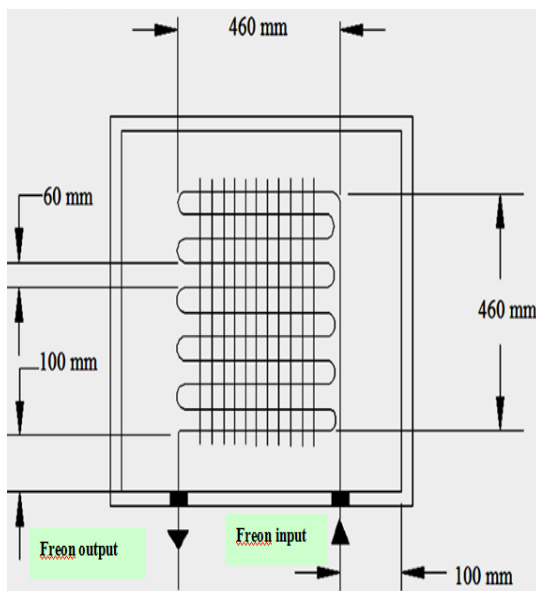


FIG. 12 DIMENSIONS OF THE REFRIGERATOR CONDENSER IMMERSED IN THE SAND FLOOR

Refrigerator and Heating Floor Coupling

For this system, the refrigerator' condenser is placed in the box filled with sand, thus, the freon condensation does not directly heat the air but the sand, and stores its heat in the heating floor (figures 13-15).

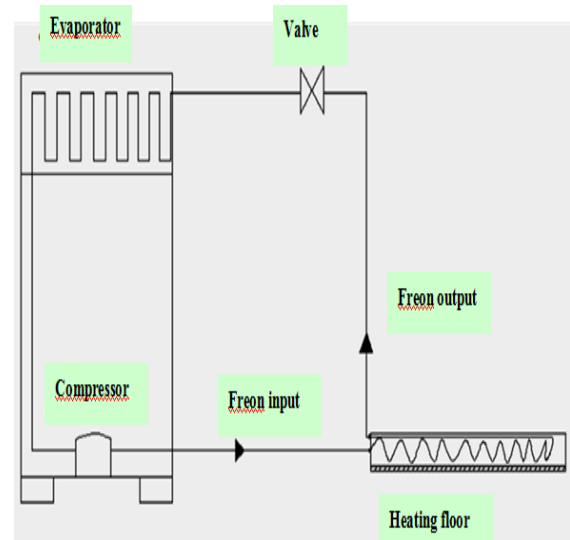


FIG. 13 INSTALLATION CIRCUIT OF REFRIGERATOR/ HEATING FLOOR COUPLING



FIG. 14 SMALL-SCALE MODEL OF THE HEATING SAND FLOOR PHOTOGRAPHS



FIG. 15 PHOTOGRAPHS OF THE TWO REFRIGERATORS: ONE COUPLED WITH THE WATER-HEATER, THE OTHER WITH THE HEATING FLOOR

Notice:

It is also possible to couple the water cumulus and the floor heating with only one refrigerator using an electromagnetic sluice gate which makes it possible to ensure the commutation of the refrigerating circuit of the refrigerator either towards the hot water cumulus, or towards the heating floor. We shall do this for comparison.

It is also to be noted that the floor can be heated in a "conventional" way by the water from big tank storage, heated by the condenser of fridges which has restaurants and hotels or refrigeration rooms of foods conservation, or other.

Experimental Results

The experiments make it possible to bind the refrigerator to the system to be heated (water and heating floor) and to record the heating, refrigeration and ambient temperatures, by probes with digital display, accuracy ± 0.1 °C.

1) Evolution of Water-heater Temperature

We study here the coupling of the refrigerator to a water heating cumulus.

a) First test

Figure 16 shows that in the morning, with the refrigerator starting, the rise in the storage water temperature is slower than that of the interior of refrigerator (approximately 8h 30 against 2h). This is because of the difference in heat mass capacity between water and air (4185 against 1000 J/kg °C).

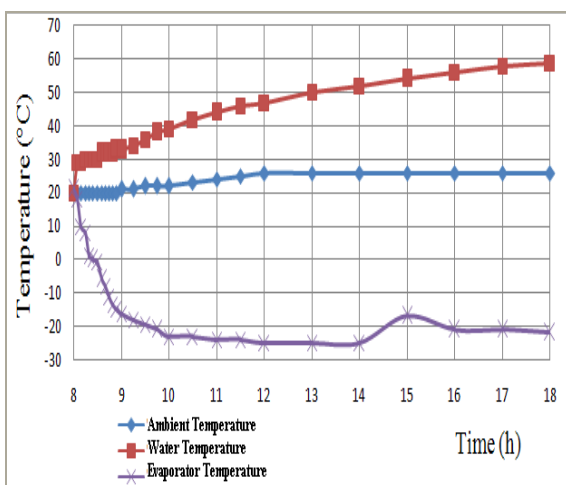


FIG. 16 VARIATION OF THE TEMPERATURES ACCORDING TO TIME. WATER HEATING CASE

With an ambient temperature of 26 °C, the water temperature reached is 59°C, that is to say a rise in water temperature of 33 °C, which is significant.

b) Second test

At the end of the one day operation, the refrigerator is voluntarily stopped for reasons of night safety. The following day at 5 am, the tests began again by the refrigerator restarting. The water temperature was 35°C, that is to say

15 °C higher than that for the previous day; showing that the cumulus stores well heat thanks to its heat insulation with glass wool.

According to figure 17, the temperature increases in the same manner than the first test, it reaches the permanent mode (59 °C) at the end of eight hours, where the thermal losses become high. A racking of ten liters hot water was carried out from the cumulus, followed by a filling of the same cold water capacity. Quickly the water temperature decreased up to 45 °C then it increased gradually to reach again the permanent mode at the end of four hours, against five hours and half for the preceding heating and the same variation in temperature. This shows that hot water can be used several times per day. Because, the mass of water heater being already hot, can be heated more quickly.

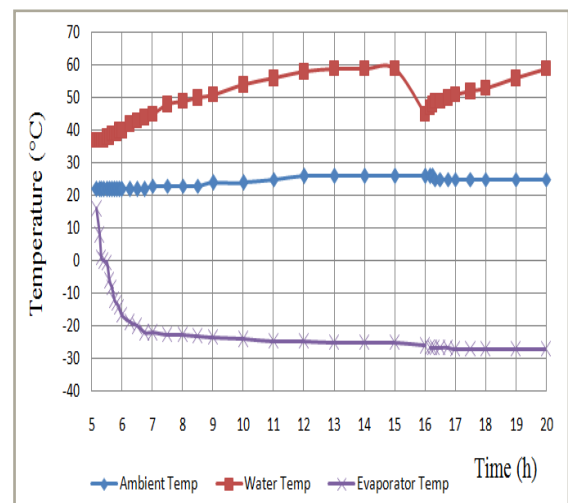


FIG. 17 VARIATION OF WATER, EVAPORATOR AND AMBIENT TEMPERATURES BEFORE AND AFTER DRAINING OF 10 LITERS WATER

2) Heating Floor Temperature Evolution

Is studied here the coupling of the refrigerator to a heated floor consisting of a layer of sand.

For the input/output curves of temperatures in the floor (fig. 18), we distinguish three zones: zones 1 and 2 without insulation and zone 3 with insulation.

- Zone 1 [5 h– 10 h]: Fast rise in floor temperatures according to time.
- Zone 2 [10 h– 14 h]: The temperatures reach their maximum values (permanent mode with 45 to 43 °C).
- Zone 3 [14 h – 20 h]: Floor temperatures rise compared to zone 2 up to 54 °C/52 °C thanks to the heat insulation.

If the heating floor is insulated, then the heat quantity stored in sand increases in a significant way, because the thermal losses are insignificant.

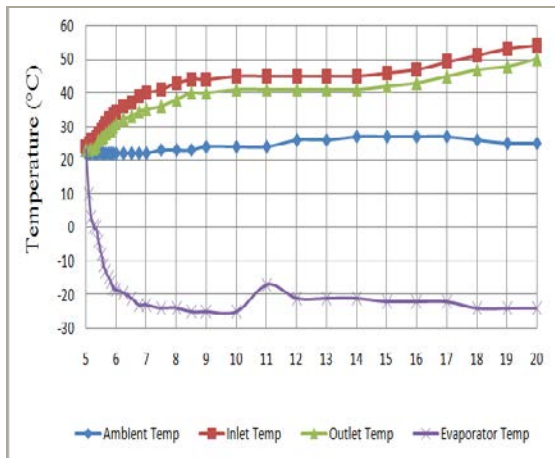


FIG. 18 TEMPERATURE VARIATION ACCORDING TO TIME. HEATING FLOOR CASE

Conclusions

By this project, we tried to widen the use of a refrigerating system for the water heating, spaces or buildings, by the exploitation of the energy previously rejected by the condenser. With this manner the refrigerator can contribute to heat water and/or floor-heating, while keeping its principal function to cool.

The temperatures reached respectively, by water and floor, are approximately 60°C and 50°C, without modifying the temperature of the evaporator, which is at approximately -20°C.

The elimination of the grid of the usual condenser located at the back of the refrigerator creates an advantage: avoiding its heating and consequently up time of the compressor and thus its electric consumption.

Finally, the results obtained as well theoretically as in experiments show clearly that the heat withdraws coming from the condenser immersed in water or in concrete, is a reliable source of heat, being able to be useful at least for pre-heating of water or room. The recovered heat enters in the negawatts production concept.

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